Select Additive Manufacturing Projects at NASA Glenn Research Center

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NASA GRC

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Outline

- Organizational Overview
  – LM – Materials and Structures Division
  – LMT – Mechanisms and Tribology Branch
  – LMA – High Temperature and Smart Branch

- EBM Feasibility of Gamma-Prime Superalloys
  – Background
  – Details

- Additive Manufacturing Structural Integrity Initiative
  – Background
  – Details
  – Planned Rheology Testing

Materials and Structures Division (LM)

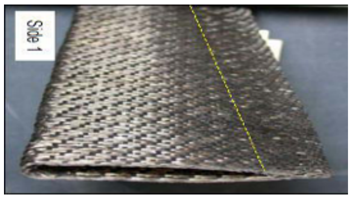
Materials and Structures Division (LM)
Dr. A. Misra
J. Zakrajsek

- **High Temperature and Smart Alloys Branch** — LMA/J. Dever, R. Carter
- **Ceramic and Polymer Composites Branch** — LMC/Dr. J. Grady
- **Structural Dynamics Branch** — LMD/Dr. D. Johnson
- **Environmental Effects and Coatings Branch** — LME/G. Robinson
- **Structural Mechanics Branch** — LMM/M. Liao
- **Materials Chemistry and Physics Branch** — LMN/R. Draper, Dr. V. Lvovich
- **Mechanical Systems Design and Integration Branch** — LMP/D. Petrarca
- **Rotating and Drive Systems Branch** — LMR/R. Handschuh
- **Multiscale and Multiphysics Modeling Branch** — LMS/G. Stefko
- **Mechanisms and Tribology Branch** — LMT/D. Ludwiczak, Dr. P. Abel

Materials and Structures Division (LM) – LMT / LMA research associated with many of these main thrusts

High Temperature Materials

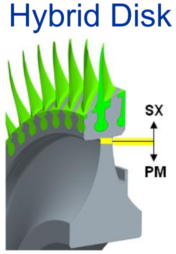
Ceramic Matrix Composite



Protective Coatings

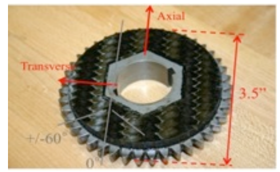
Thermal Protection Seal

Hybrid Disk

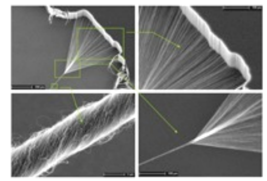


Lightweight Concepts

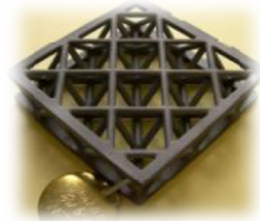
Hybrid Composite Gear



Nanotube Yarn



Lattice Block

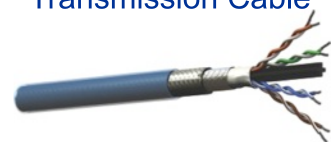


Flexible Aerogel

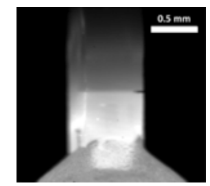
Electric Propulsion Materials

Materials for High Power Density Electric Motors

Lightweight Power Transmission Cable



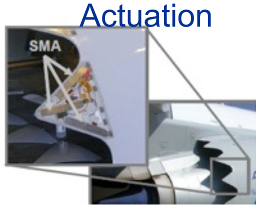
Silicon Carbide Semiconductor



Mechanisms and Drive Systems

High Efficiency Gear

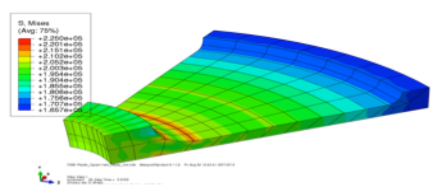
Shape Memory Alloy-Based Actuation

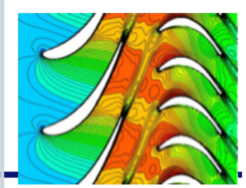


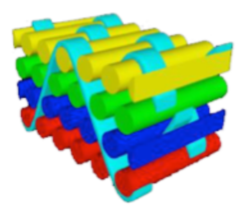
Superelastic Bearing

Spring Tire

Computational Modeling

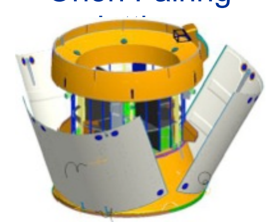






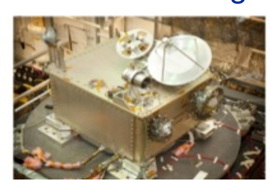
Flight Structures

Orion Fairing

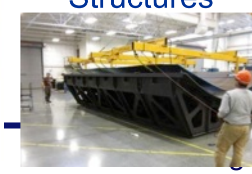


Low Impact Docking Seal

Vibration Testing



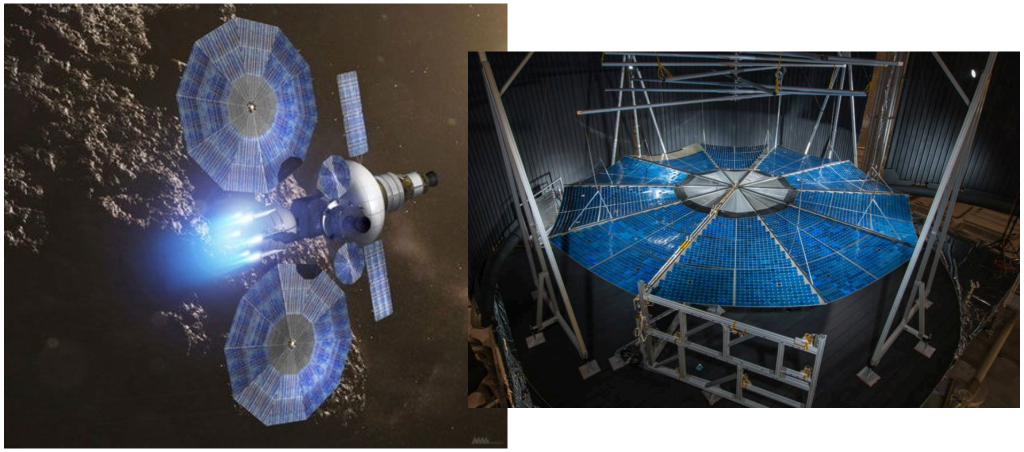
Large Composite Structures



LMT: Mechanisms and Tribology Branch - Key Thrust Areas

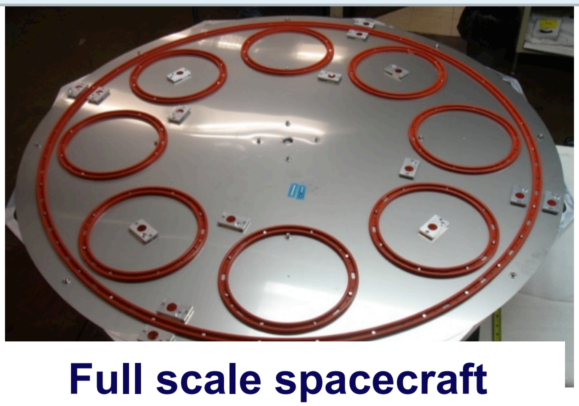
Space Mechanisms

Orion Spacecraft



Large Deployable Space Arrays

Aerospace Seals Research



Full scale spacecraft docking seals for JSC

Advanced Bearings

Patented super-elastic 60NiTi bearing balls, and first Nitinol hybrid bearing

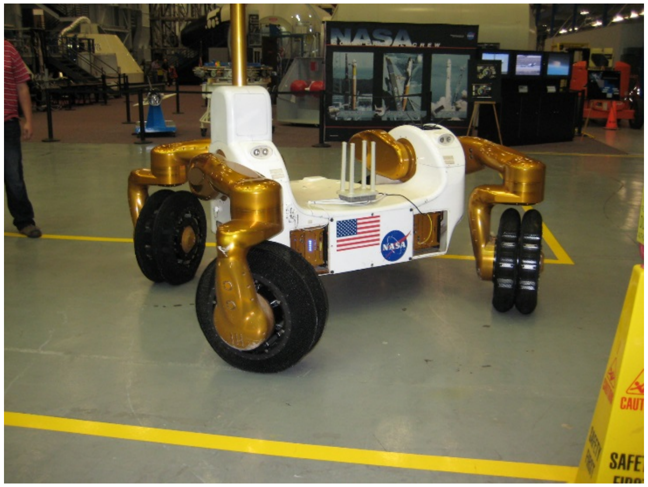
LMT key thrust area: Planetary Surface Mobility

Current Technical Focus

Development of advanced traction methods and mechanisms for negotiation of extreme planetary terrains.

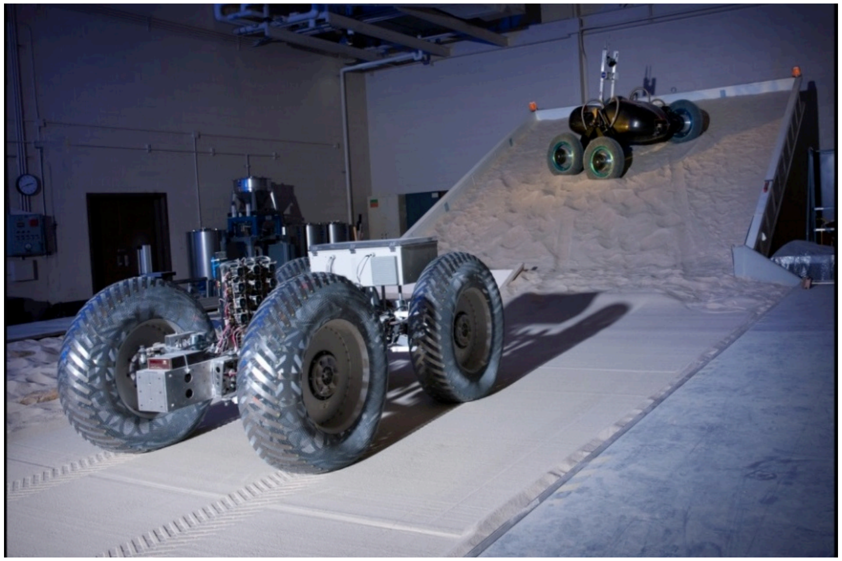
Recent Success

Demonstration of 2nd generation excavator for JSC Centaur 2 Rover



Demonstration of new high load capability "spring tire"

Unique Experimental Capabilities - Surface Mobility



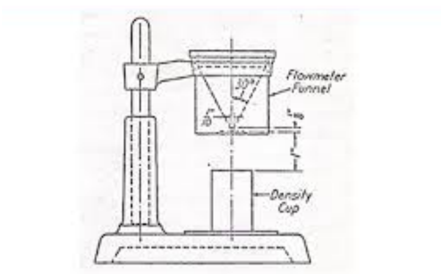
SLOPE Laboratory

TRaction and Excavation Capabilities (TREC) Rig

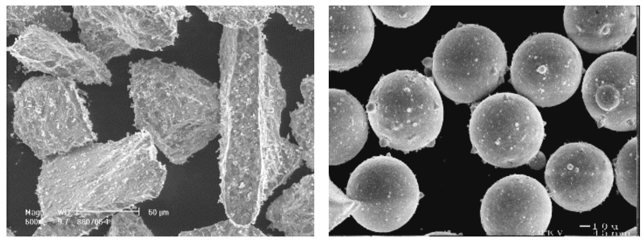
The Dunes Test Area

Powder Rheology

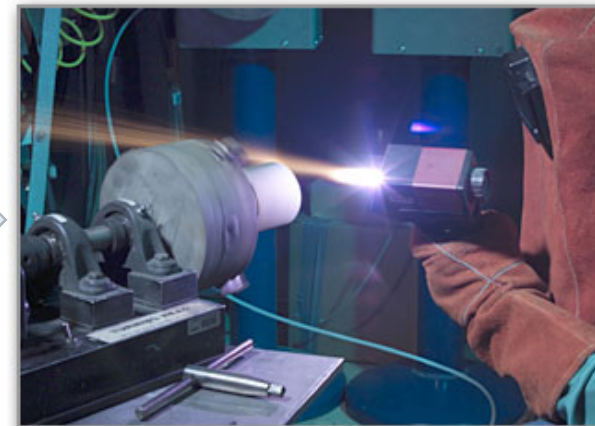
Powder characterization in the group has been done to support the larger technology areas



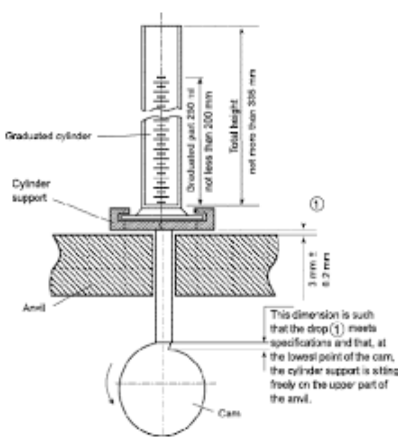
Hall flowmeter



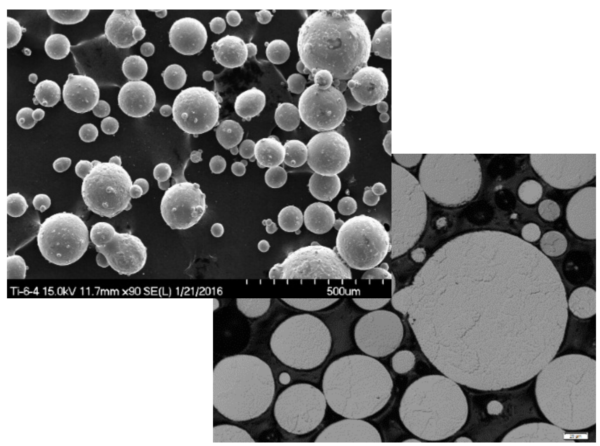
Ceramic powder made by a new technique for better flowability…



…to commercialize NASA thermal spray coatings



Tapped density



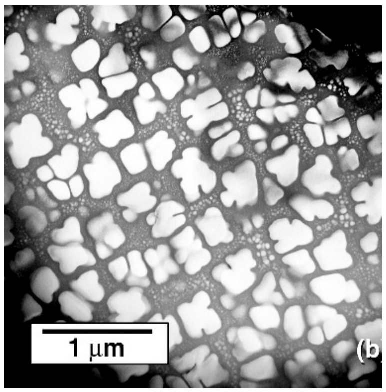
Metallic powders for HIPping

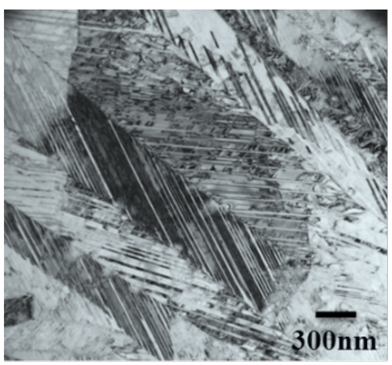
HIPped bearing races

High Temperature and Smart Alloys Branch (LMA)

Applications

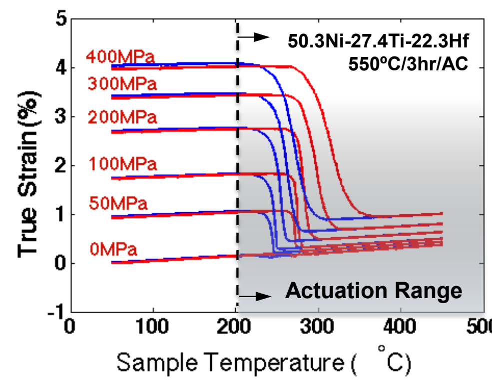
- Hot Sections of Turbine and Rocket Engines
- Actuators and Energy Absorbing Components
- Power System Conductors and Magnets
- Applications Engineering for Space Systems





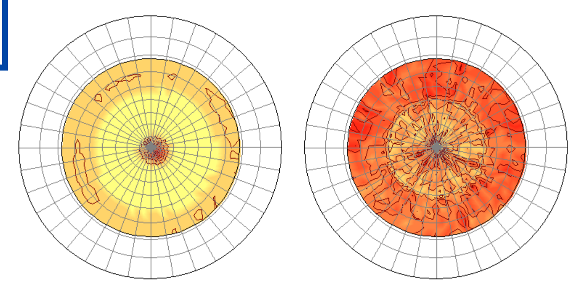
Research Focus Areas

- **Superalloys**
- **Copper Structural Alloys**
- **Shape Memory Alloys**
- **Conductor and Magnetic Alloys**
- Alloy development
- Additive manufacturing
- Structural concepts
- Bonding/Joining
- Mechanical behavior/performance
- Computational modeling



Laboratory Capabilities

- **Processing**
- **Testing**
- **Characterization**

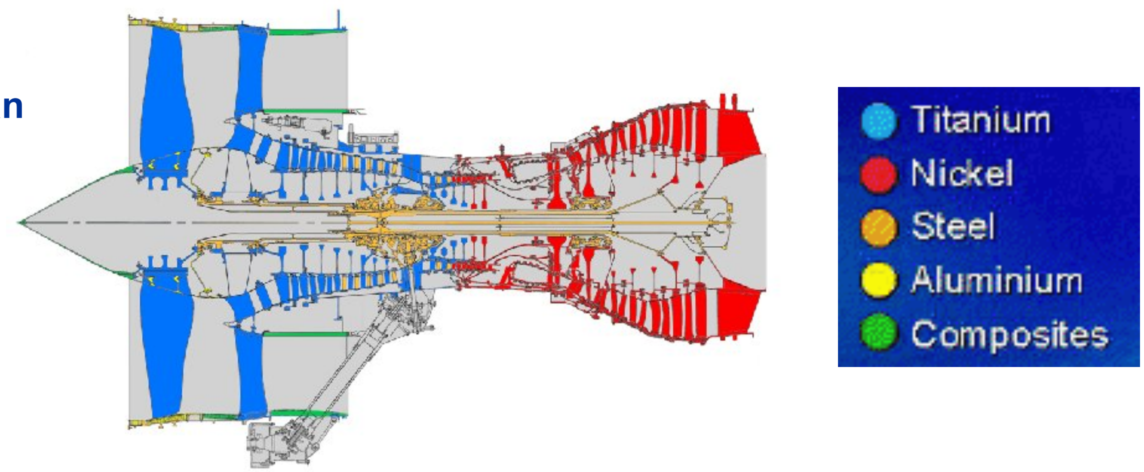


EBM Feasibility of Gamma-Prime Superalloys

Ni-based γ'-superalloys used for most demanding environments in gas turbine engines for commercial and military aircrafts

50 % or more of the engine weight is from nickel alloys

Turbofan



Other uses → inter and intra-agency interest:

- **Next generation nuclear reactors**
- **Land based gas power generation**
- **Turbopumps for rocket engines**
- **Marine gas engines**

Scale down: e.g., high OPR small-core gas turbine

- *Investment casting cost effective for high production (100,000 parts / year)*
- *Target low production to avoid custom made tooling & intricate structures*
- *Turbomachinery: Cooling efficiency, materials by design, integrated designs*

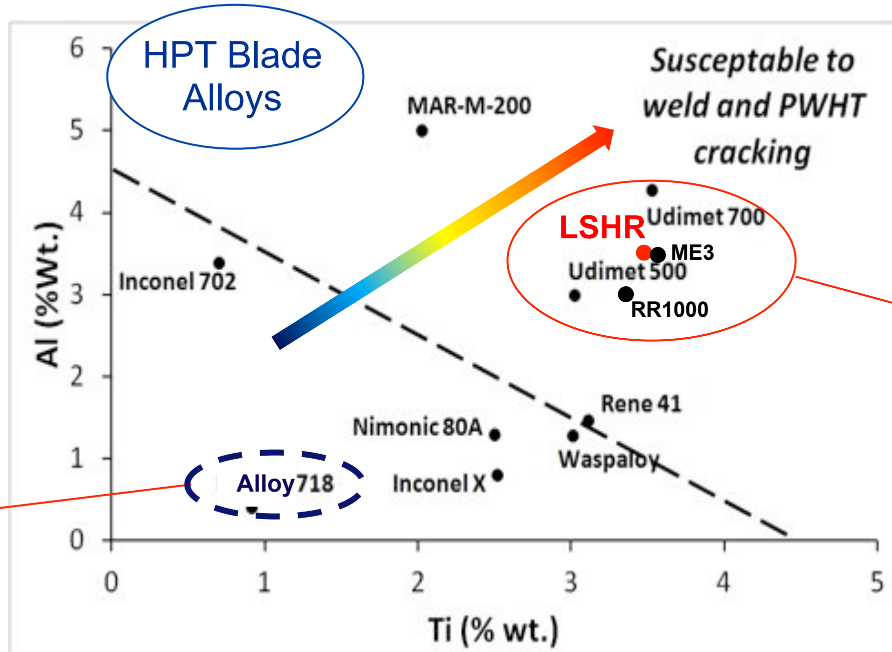
Metals AM is rapidly advancing, still limited to primarily 30 common alloys

Goal: Ascertain feasibility of AM for high-temperature Ni-based superalloys with LSHR

Weldability of Ni-based superalloys

Only 30 alloys common to AM

Maturing Technology



Adapted from: LN Carter, MM Attallah, RC Reed, Superalloys 2012 (2012) pp. 577-608

HPT Disk alloys

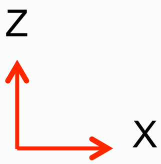
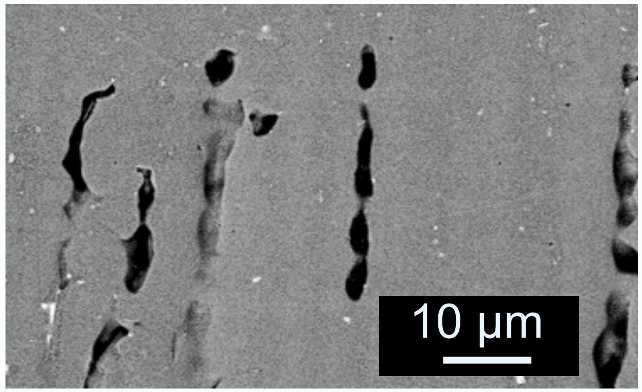
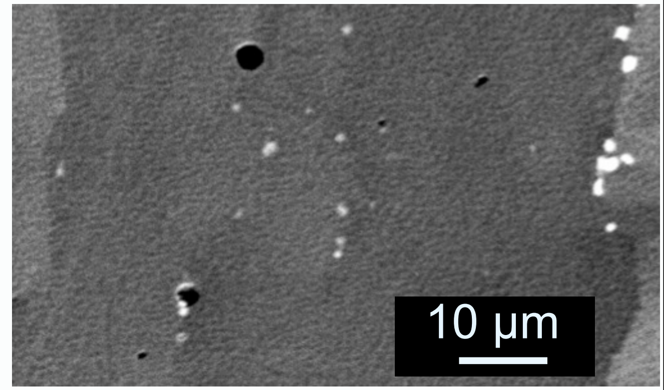
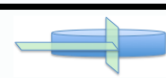
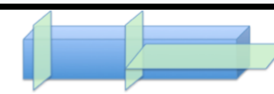
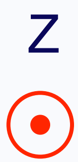
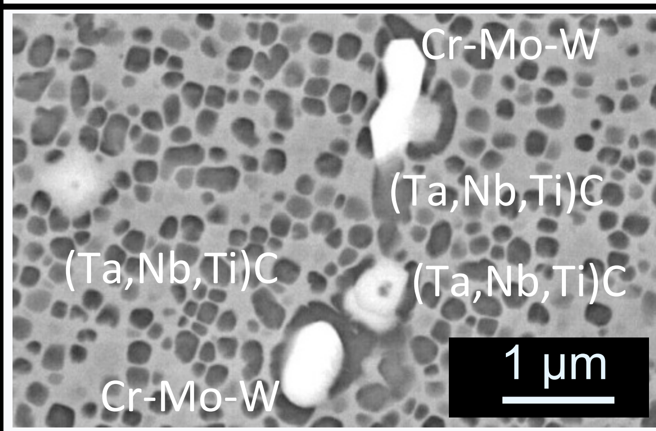
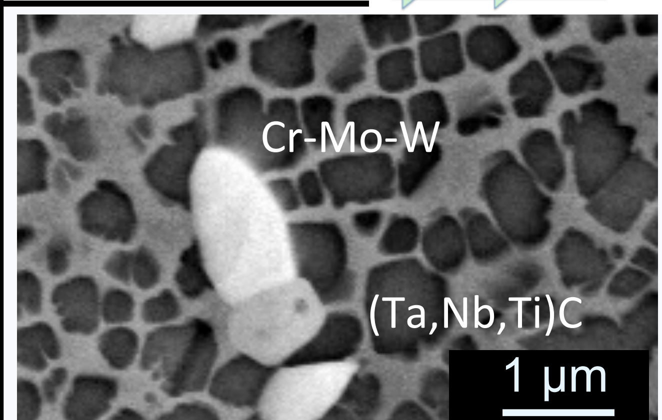
Other alloys need feasibility assessments and more R&D

<u>LSHR compared to Alloy 718 has:</u>

- Higher temperature long-term stability and mechanical durability → HPT disks
- Higher risk of cracking during rapid solidification
- Poorer weldability

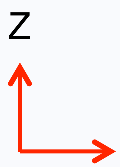
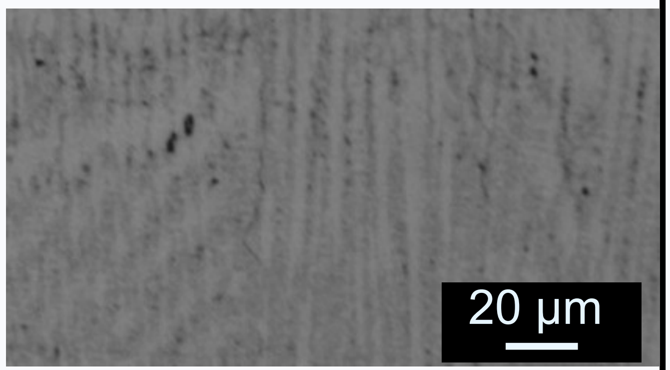
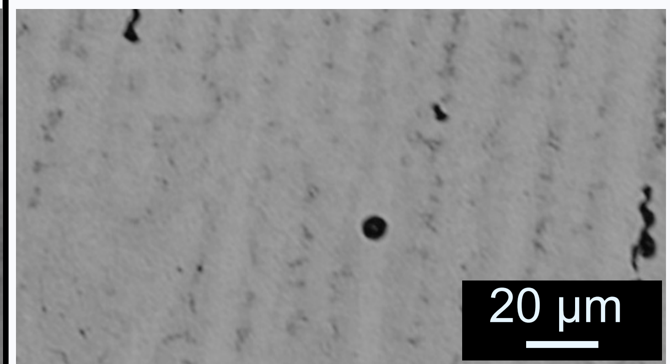
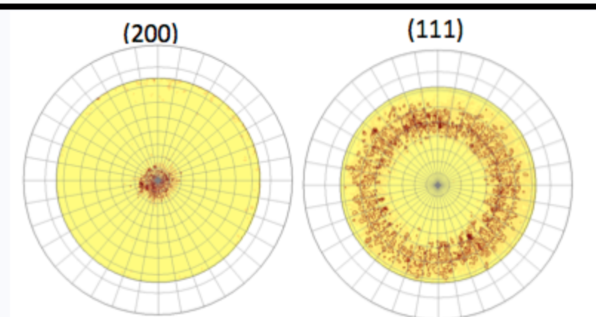
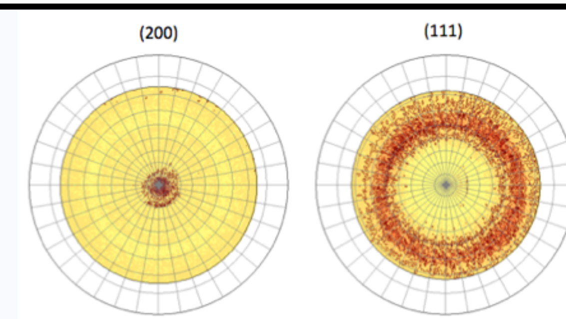
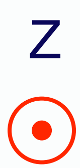
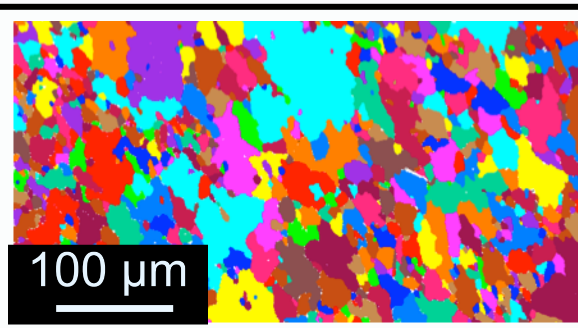
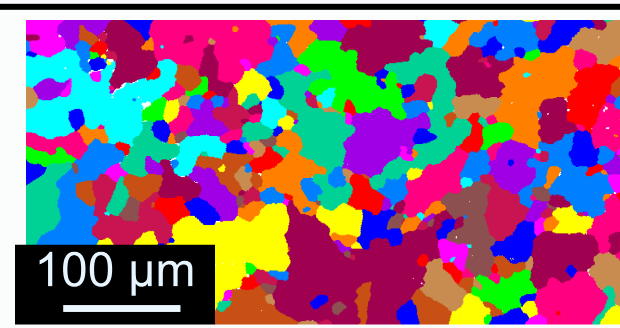
→ Reduce cooling rate

Side by side comparison of as-fabricated EBM pieces

Interior Areas	Small Buttons 19 mm (diam.) x 4 mm (H)	Rectangular Blanks 16 mm x 79 mm x 18 mm (H)
Porosity	Comparable	Comparable
 Process-induced porosity		
Cracking	No evidence	Half dozen confined to the top of build, 2.1-4.3 mm
Avg γ'-ppts cube length	110-150 nm 	240-360 nm 
Precipitation Minor phase coarsening 		

OAK RIDGE National Laboratory

Side by side comparison of as-fabricated EBM pieces

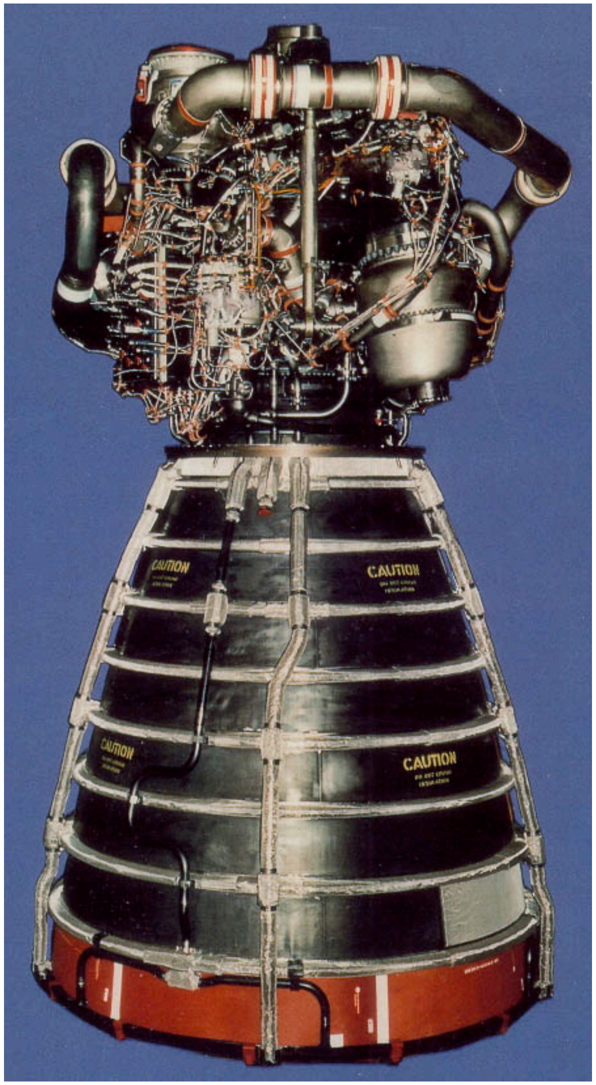
Interior Areas	Small Buttons 19 mm (diam.) x 4 mm (H)	Rectangular Blanks 16 mm x 79 mm x 18 mm (H)
Highly oriented, fine dendritic structure 		
Avg grain diam 2D	About 10 µm	Increased by 1.5 times
Columnar grains with (001)-fiber texture 		
Transverse EBSD maps - 2D grain diameter 		

Oak Ridge National Laboratory

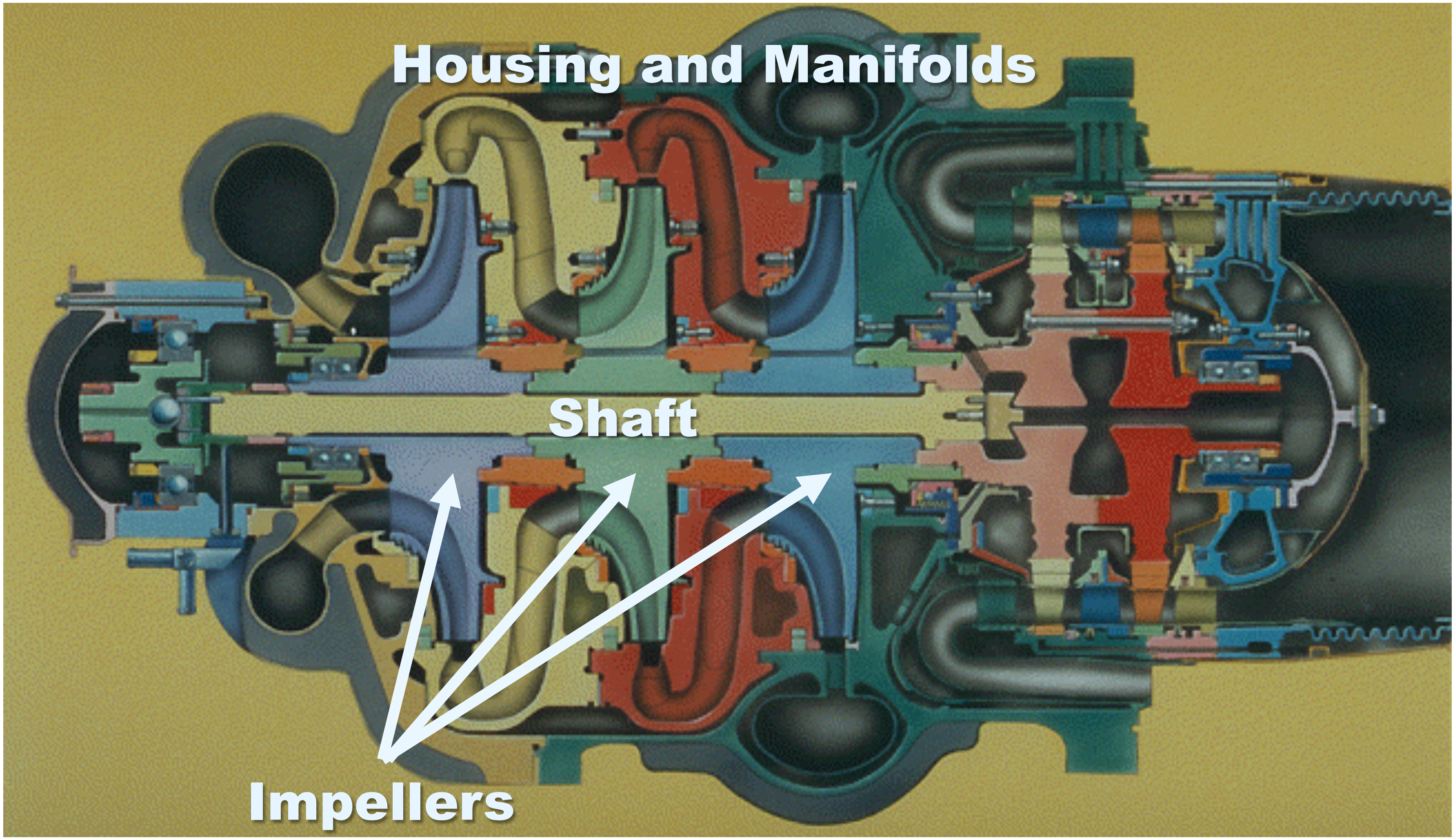
Additive Manufacturing Structural Integrity Initiative (AMSII)

Additively Manufactured IN-718 Parts For The RS-25E Engine

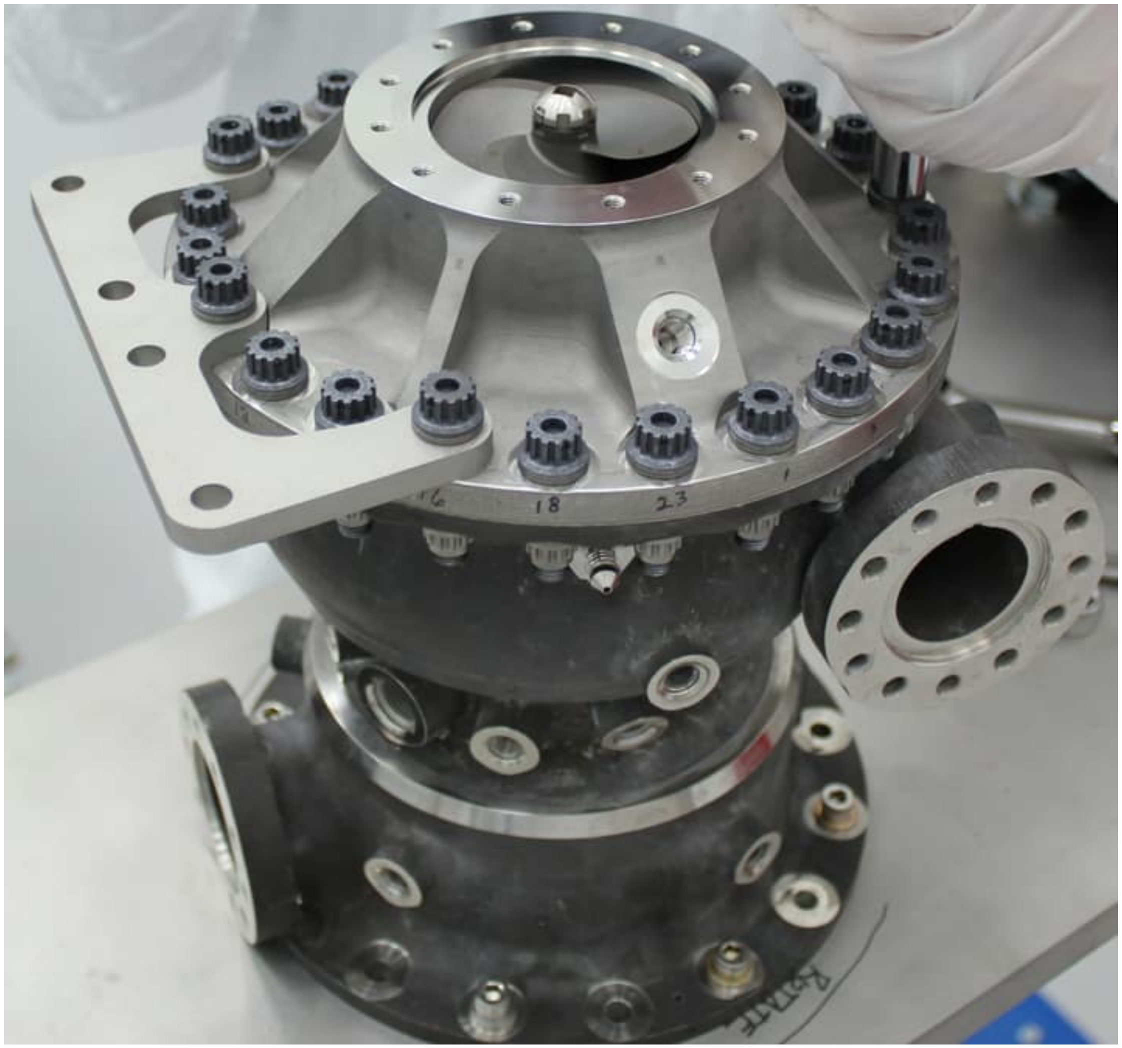
- Derivative of RS-25 Space Shuttle Main Engine (SSME)
- LH2/LOx engine
- 418,000 lb_f sea level / 512,300 lb_f vacuum
- Length – 618 in.
- Diameter – 96 in.
- Weight – 7,775 lbs
- ***At least a couple dozen components are targeted to be additively manufactured***



Example Application:
Fuel Turbopump (FTP) Parts

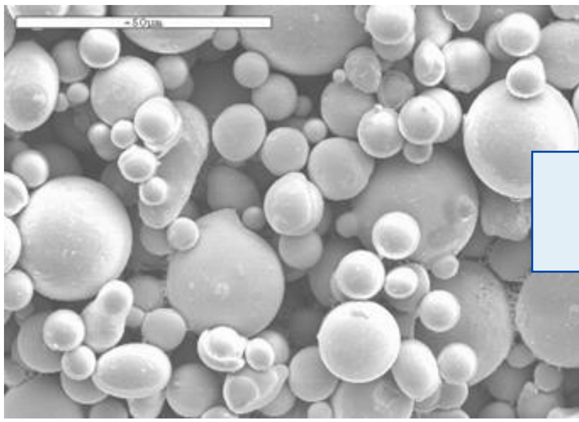


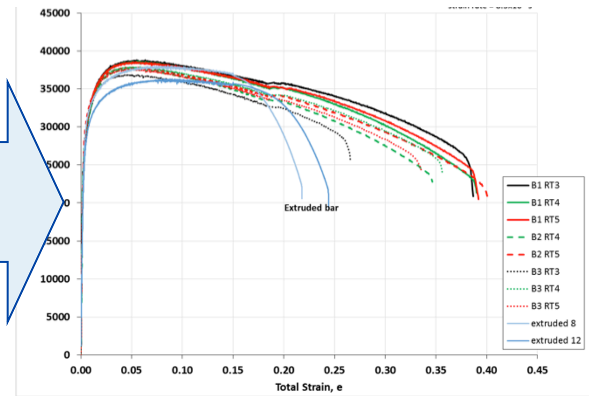
3D Printed Rocket Components Are Already A Reality



- FTP for 30,000 lb_f class rocket engine
  - Suitable for upper stage engine
- 90,000 RPM disk speed
- 45% fewer parts than SSME FTP
- Tested under actual service conditions in July 2015 at NASA MSFC

Additive Manufacturing Structural Integrity Initiative (AMSII)





AMSII is taking a holistic approach to additive manufacturing from powder to processing to properties

Major Goals:

1. Develop feedstock controls and maximum recyclability limits
2. Identify powder control and heat treatment metrics for inclusion in standard for RS-25E Engine

Overview Research Plan For AMSII

1. **Powder Characterization**
   A. Size distribution
   B. Morphology
   C. Rheological properties
   D. Post-use changes / reusability
2. **Manufacturing**
   A. Powder bed characterization
   B. SLM parameters
   C. Melt pool modeling
   D. HIP parameters
   E. Microstructural modeling
3. **Consolidated Properties**
   A. Microstructure
   B. Mechanical properties such as tensile, creep and fatigue strengths
   C. Flammability

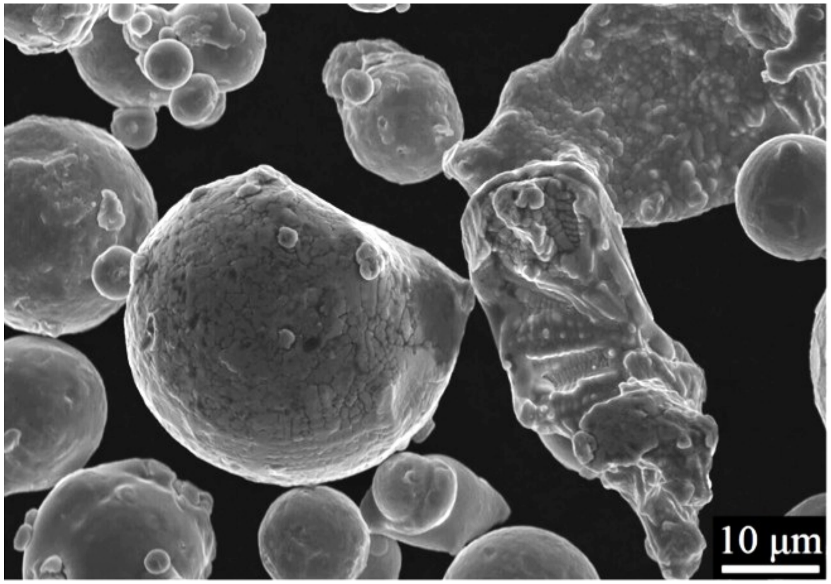
Production Lot Comparison - Chemistry

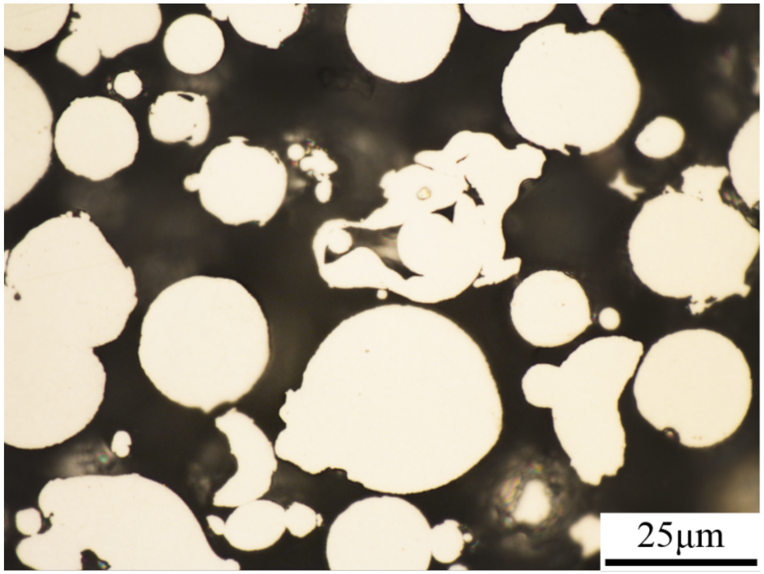
- Powder lot #1 and #2 showed significant variations in Si and N content with a balance offset in Ni
- Overall powder lot #2 had slightly higher levels of trace impurities due differences in processing

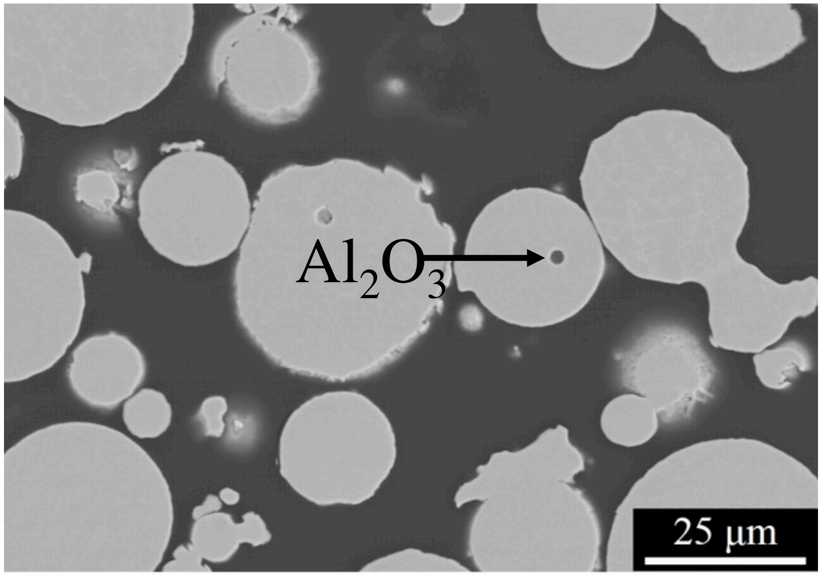
Major Elements, wt%									Minor
Element	Ni	Al	Co	Cr	Fe	Mo	Nb	Ti	C
Standard	50-55	0.2-0.8	≤1.0	17-21	Bal.	2.8-3.3	4.75-5.5	0.65-1.15	≤ 0.08
#1	52.85	0.50	0.10	19.11	18.54	2.96	4.93	0.82	0.035
#2	53.55	0.39	0.17	18.37	18.46	2.97	4.97	0.92	0.034
Δ	+0.7	–0.11	+0.07	–0.74	same	same	same	+0.10	same
%Δ	+2.5%	+22	+70	–3.9	n/a	n/a	n/a	+12.2	n/a

Trace Impurities, wt%										
Element	Cu	Mn	Si	V	W	N	O	Ca	Na	Zr
Max	≤ 0.3	≤ 0.35	≤ 0.35	0.010	trace		0.020			
#1	0.02	0.030	0.02	0.01	0.015	0.012	0.019	0.00305	0.003	0.003
#2	0.03	0.045	0.05	0.02	0.025	0.037	0.022	0.00095	0.002	0.005
Δ	+0.01	+0.015	+0.03	+0.01	+0.010	+0.026	same	-0.00210	0.001	-0.002
%Δ	+50%	+50	+150	+100	+67	+216	n/a	–68	–33	+67

Powder Lot 1

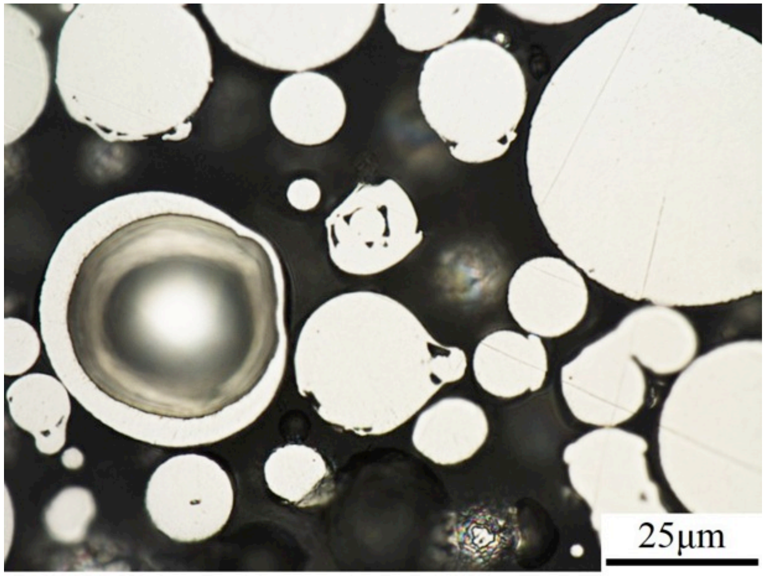


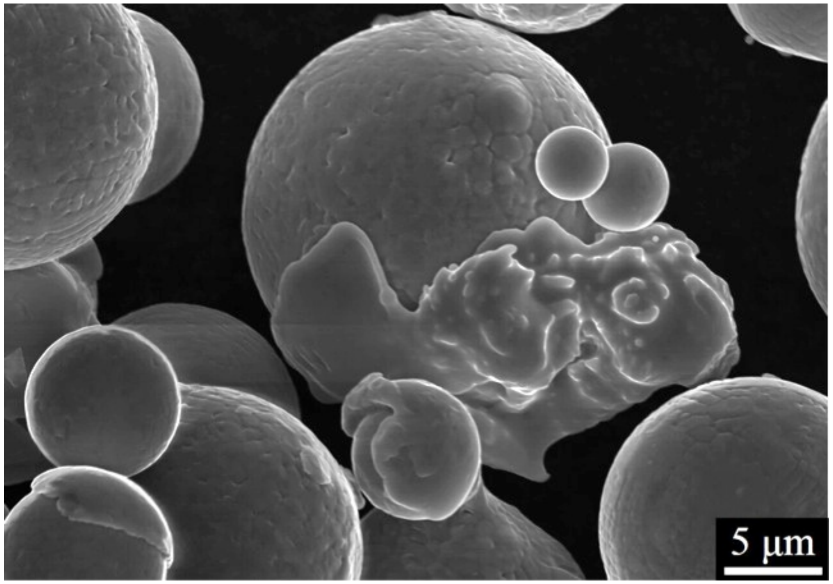


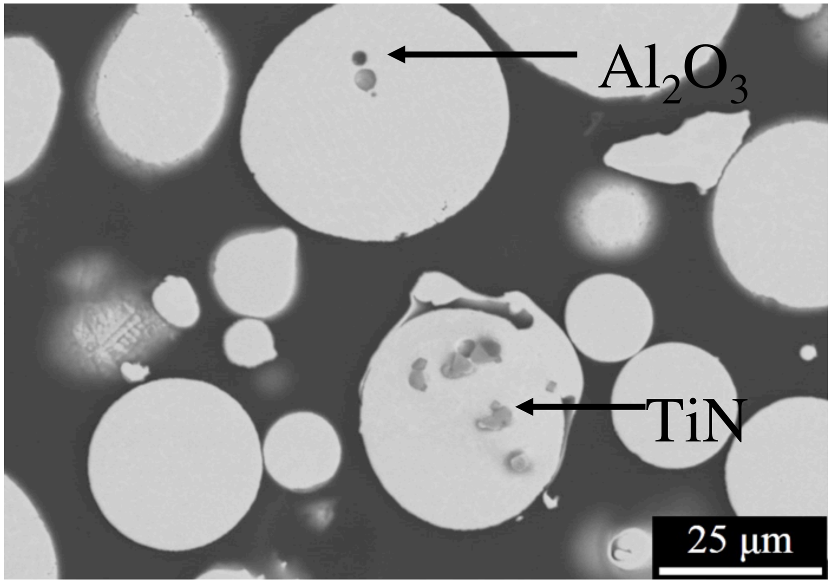


- Powder agglomeration were observed with some porosity retained
- Some irregular sized particles were observed in the sample
- Not many NMI's were observed

Powder Lot 2







- Some powder satellites and small agglomerations attached to powder surfaces
- Inclusions were readily observed in a high frequency

Production Lot Comparison

Powder Lot	Trace Elements	Morphology	Agglomeration	Smoothness	GA Porosity	PSD
1	Lower trace elements	Higher frequency of non-spherical particles	Larger aggs.	Rough surface and satellites	Only fine porosity observed	Narrow distribution
2	Increased residuals from Cu, Mn, Si, V, N O, Ca than Carp.	Lower frequency of non-spherical particles	Finer aggs. with minor pores	Smooth surface with some satellites	Large and fine porosity regularly observed	Broader distribution

- Size of pores associated with gas atomization were larger for powder lot #2, with some pores as large as 20 µm
- Trace impurity content and the number density of inclusions is higher for Powder Lot #2
- Powder Lot #1 does appear to be less smooth, less spherical and have higher frequency of agglomeration than Powder Lot #2

Approach

- Screening Study
  - Order 50 lb powder lots from vendors that supply off-the-shelf 718 powder (GOAL: 10-12 lots)
  - Analyze powder properties
  - Fabricate test pieces with SLM
  - Microstructure evaluation
  - Assess tensile and fatigue properties and failure mechanisms
- Down-select 3-4 conditions for full investigation
  - 500 lb powder lots
  - Recycled properties

AMSII Interest In Freeman Technology FT4 Unit For Rheology Testing

- Wall friction, confined flow and unconfined flow for delivering powder to the powder bed
- Consolidation, density and compressibility to characterize the powder bed
- Flow (shear) sensitivity, shear testing and wall friction for raking powder in powder bed
- Caking, moisture effects, segregation, attrition, electrostatics and agglomeration for powder bed and powder reusability characterization